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C26A26

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CAPACITOR FAILURES - KELSEY-HAYES

G.K. Hatanaka

Tests have been performed at Kelsey-Hayes to investigate a problem involving power factor correction capacitor failures. Measurements were performed on a new production line that supports several induction motors individually corrected for power factor. A number of ac and dc welders operate on the same supply. Test results indicate that the capacitors are overloaded due to harmonic currents generated during welding operations. The conditions are exacerbated due to a resonant condition close to the 11th and 13th harmonics. The total rms capacitor current can exceed the CSA Standard limit of 135% of rated current including the effects of harmonics for continuous operation. Because of the "on-off" non-continuous duty cycle of the welders, it is not clear whether the harmonic overload condition is within the capability of the capacitors. Possible solutions are outlined.

1.0 INTRODUCTION

Kelsey-Hayes in Windsor, Ontario is a manufacturer of car wheels and has been experiencing problems with failed power factor correction capacitors. At the request of Commercial/Industrial Marketing, Marketing Operations Division, the Electrical Research Department has performed an investigation to help the customer resolve the problem.

The customer operates a number of both ac and dc welders that are non-linear loads and known to generate harmonic currents. It is recognized that excessive harmonic conditions often lead to equipment damage or failure. Therefore, the investigation focused on this possibility. Appropriate tests were performed on April 22 and 23, 1987. This report summarizes the test results.

2.0 HISTORY OF PROBLEM

The customer is presently operating a new production line that includes several hydraulic pump motors which are individually corrected for power factor. Dry type capacitors were specified by the customer and supplied from the USA with the motors. Two capacitors have failed on this line.

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Capacitors have also failed in other parts of the plant but there is no detailed documentation on these failures. Sometimes they would be left disconnected and not reported or changed by maintenance staff before the problem could be investigated.

The new production line is the only line where capacitors are connected to each motor. The rest of the plant does not make extensive use of power factor capacitors. The customer would like to add capacitors to the rest of the plant during regular equipment maintenance but does not plan a specific program.

3.0 SUMMARY OF TESTS

The tests were confined to the customer's new production line which supports 10 hydraulic pump, induction motors individually corrected for power factor. Each capacitor is switched in and out with the motors. The line is fed from a 27.6 kV/575 V, Δ/Δ connected transformer which also supplies two 3-phase rectified dc welders and 10 single-phase ac welders. The rest of the plant is fed off two separate supply transformers.

A number of measurements were performed at three selected motor/capacitor units with different hp/kVar ratings and at the line side of one of the dc welders. The dc welders are identical and are designated 'A' and 'B'. Measurements were performed on 'A'.

Three phase voltage signals were conditioned using step down transformers (nominal ratio of 720:120) connected delta-wye grounded. Each phase was measured in turn using a calibrated 100X probe. The currents were measured using a clamp-on CT (BAUR VZ600/10-600 A).

Voltage and current waveforms were observed on the Tektronix 468 digital storage scope and harmonic analysis was performed using the HP3562A Dynamic Signal Analyzer. Each measurement on the HP3562A consisted of a single RMS average using the flat top window. The digitized data was stored directly to a 3-1/2 inch disk drive for further analysis in the laboratory. RMS voltage and current were also measured on the Beckman RMS3030, true rms responding DVM.

The current was also monitored on the HP3400A rms voltmeter and a continuous measurement of current amplitude vs time was recorded on the Mosely 680M strip chart recorder.

4.0 TEST RESULTS

Figures 1 to 3 show photographs of typical waveforms at the dc welder and at three different motor/capacitor units.

Figures 4 to 8 show the corresponding harmonic spectra during operation of the welders.

4.1 DC Welder Waveforms

An example of the bus current and voltage waveforms at the dc welder are given in Figure 1. Only I_r and V_r-w are shown. The other two phases are similar. The waveforms are severely distorted and very rich in harmonics as shown in Figure 4.

The predominant current harmonics are numbers 5, 7 and 11, 13 and 17, 19 etc and decrease in amplitude with increasing harmonic number. The evens are missing and the triples are very low. This is typical of a 6 pulse rectifier. The harmonic spectrum of the voltage waveform shown in Figure 4 exhibits amplification of the 11th and 13th harmonics which indicates a resonant condition on the bus.

4.2 Capacitor Waveforms

The current and voltage waveforms at three motor/capacitor units are shown in Figure 2 during the operation of the 3-phase dc welder. The combinations include 10 hp/3 kVar, 30 hp/7 kVar and 40 hp/11 kVar. In each case the current waveform is severely distorted due to the high harmonic content when the dc welder is operated. Results are shown for one phase. The other phases should be similar.

The capacitors act as a sink for the harmonic currents and the problem is exacerbated by the resonant condition which is evident by the "peaking" close to the 11th and 13th harmonics in the corresponding harmonic spectra shown in Figures 5 to 7.

Figure 3 shows the three phase capacitor waveforms for the 10 hp/3 kVar unit during the operation of a single ac welder located closest to the measurement point. Because the ac welder operates on a single phase, the harmonic currents are in this case unbalanced. The harmonic content on the phase with the ac welder, however, is similar to the dc welder case and is shown in Figure 8.

4.3 Capacitor Waveform Quantities

Table 1 summarizes 60 Hz and composite waveform quantities at the capacitors that can be used to assess the overall harmonic conditions during operation of the ac and dc welders.

The results have been derived from the spectrum analysis of voltage and current on the HP3582A. The HP3582A automatically calculates the total harmonic distortion (THD) on the first 20 harmonics (up to 1260 Hz) as follows:

$$THD = \left(\frac{\sum_{h=2}^H W_h^2}{W_1^2} \right)^{1/2} \times 100\%$$

where W_h is the harmonic voltage or current
 W_1 is the fundamental (60 Hz) voltage or current
 h is the harmonic number, an integer.

The rms quantities for the composite waveforms and the apparent power VA were also calculated from the individual harmonic components.

The values in the Table are given in per unit (pu) using the rated voltage (600 volts) and current (based on the rated kVar) of the capacitors as the base.

Table 1

Waveform Quantities

<u>HP/KVar</u>	<u>Welder</u>	<u>Phase</u>	<u>THD in %¹</u>		<u>60 Hz in PU²</u>		<u>Composite Including Harmonics in PU²</u>			
			<u>V</u>	<u>i</u>	<u>V</u>	<u>i</u>	<u>VAR³</u>	<u>V</u>	<u>i</u>	<u>VAR³</u>
10/3	?	b	9.95	89.6	0.94	0.84	0.79	0.94	1.12	0.86
10/3	dc	r	9.09	108.0	0.93	0.82	0.77	0.93	1.21	0.84
10/3	ac	b	7.91	83.9	0.94	0.88	0.82	0.94	1.15	0.88
10/3	ac	r	1.77	20.9	0.95	0.92	0.87	0.95	0.94	0.88
30/7	dc	r	8.26	106.0	0.93	1.00	0.94	0.93	1.46	1.01
30/7	dc	b	8.39	100.0	0.93	0.96	0.89	0.93	1.36	0.96
40/11	dc	r	8.39	103.0	0.94	0.93	0.88	0.94	1.34	0.95

1. Total Harmonic Distortion, THD is given in % of the fundamental or 60 Hz value.
2. Base values are the rated voltage (600 V) and rated current calculated from the rated KVar for each capacitor unit (ie, 2.89 A for 3 kVar, 6.74 A for 7 kVar and 10.58 A for 11 kVar).
3. The capacitor is assumed to be a pure reactance.

The results of Table 1 are examples of the highest levels of distortion measured on the HP3562A during the testing period. These were from a number of sampled readings. However, the continuous recording of rms current indicates that higher or lower levels can occur during the welding operations as described below.

4.4 Welding Operation

During a production run any of the ac welders or dc welders may operate. Each operation lasts about 1 s with a quiescent period in between. The operation is cyclic, about every 2-3 seconds but somewhat random. This is shown in Figure 9 which is a sample of the continuous recording of total rms capacitor current during the test period at the 10 hp/3 kVar motor capacitor unit. Each time a welder operates, the rms capacitor current increases above the normal operating current during the quiescent periods between welding operations. This results in an overload current which is both random and repetitive in nature.

The overload occurs each time a welder operates but the overload levels vary. These appear to depend on which welder operates and if it is an ac welder, what phase it is on and where it is located. In Table 1 the highest level at the 10 hp/3 kVar unit taken from the sampled measurements on the HP3562A was 1.21 per unit (121% of rated). However, the continuous recording shows that higher levels occasionally occurred. Figure 9 shows a few successive operations which exceed 135% of the rated current. These are suspected to be operations of the dc welder. Figure 9 shows also two operations which produced overload levels of 1.74 and 1.62 per unit. It is suspected that these higher levels are the result of a combination of certain welders operating simultaneously.

Similar results of continuous recordings on the 30 hp/7 kVar limit showed that the 135% limit was generally exceeded during welder operations. Continuous data was not obtained for the 40 hp/11 kVar unit.

These results describe the typical nature of the overload conditions but are not necessarily normal. The dc welders on the new production line were not in a full production cycle and were "down" during much of the measurement period as they were being adjusted. When the dc welders were "up" they operated approximately every 5 seconds.

5.0 ANALYSIS OF RESULTS

5.1 Effect of Excessive Harmonics

The measurements show that considerable harmonic currents are generated whenever the ac or dc welders are operated. The levels vary and depend on which welders are operated at any given time. The capacitors act as a sink for the harmonic currents and therefore, carry total rms current in excess of the rated 60 Hz current during the welding operations. The excess current levels are exacerbated by a resonant condition close to the 11th and 13th harmonics.

The flow of the harmonic currents results in harmonic voltages and produces extra power losses in the capacitors which may lead to a temperature rise problem. In addition, the total reactive power, including the fundamental and harmonics will be increased.

5.2 Standards on Capacitor Performance

In Canada, industrial capacitors intended for power factor correction are covered by CSA Standard C22.2 No 190-M 1985/1/ which calls up CSA Standard CAN3-C155-M84/2/ on shunt capacitors for a description of ratings. In the USA, shunt capacitors are covered by IEEE Standard ANSI/IEEE Std 18-1980/3/.

Capacitors that meet the requirements of CAN3-C155-M84 should be capable of continuous operation

- i) at 110% of the rated rms voltage including harmonics.
- ii) at 135% of the rated rms current (capacitors rated less than 2400 V) including fundamental and harmonic currents.
- iii) at 135% of rated reactive power (kVar) including the combined effects of reactive power due to:
 - voltage in excess of rated voltage within the limits of i)
 - harmonics
 - capacitance in excess of rated capacitance within an acceptable tolerance of 0 to +15%.

5.3 Evaluation of Capacitor Overload Conditions

The total rms voltage including the effects of harmonics is well within the CSA requirements of 110% rated voltage. The capacitors operate at less than the rated capacitor voltage of 600 volts since the supply voltage is stepped down to meet the 575 volt operating voltage rating for the induction motors.

Because each capacitor operates at less than the rated voltage, the reactive power including harmonics is considerably lower than the maximum permissible in the CSA standard and generally less than the rated output.

The total rms current, however, exceeds rated current during the welding operations and can approach or exceed the maximum permissible CSA requirement of 135% rated current during some of the operations. This is particularly true during the operation of a dc welder. However, the welding operations are not continuous but rather quasi-continuous or repetitive in nature with a low duty cycle, perhaps in the order of 20%.

It is difficult to assess the severity of the harmonic conditions in relation to the CSA performance requirements. Because the operation of the welders is not continuous, a strict interpretation of the CSA standard cannot be made. The capacitors should operate satisfactorily under the existing conditions in terms of voltage and reactive power. However, the harmonic current overload results in increased power losses that could lead to increased temperature rise and blowing of fuses. In addition the overheating may result in gradual deterioration and shortened life of the capacitor.

5.4 Expected Capacitor Performance Under Overload Conditions

Several factors make it even more difficult to assess the capacitor overload problem.

First, manufacturers are not required to supply capacitors that meet the CSA standard.

Second, it is still not clear whether capacitors, that are claimed to meet the CSA standard will in fact perform in accordance with the required performance specifications for continuous operation as summarized in Section 5.2 above. This is because it is difficult to perform suitable tests to show compliance with these requirements and an established test procedure has not been specified in the standards. (CSA standard C22.2 No. 190-M 1985 is currently under review and it is our understanding that the focus will be on resolving some of the issues surrounding these performance requirements.)

Third, the requirements do not necessarily preclude gradual degradation and a shortened life expectancy.

5.5 Possible Remedial Measures

The analysis suggests that if the installed capacitors are designed to meet the performance requirements of existing industry standards (CSA and IEEE), remedial measures should not be required to operate continuously under the measured conditions. However, given that same form of gradual deterioration can still be expected or that the capacitors may not be suitably rated, a number of remedial measures are available:

- install capacitors with higher voltage rating
- install capacitor/reactor units to reduce the magnitude of harmonics due to resonance
- install capacitors with different reactive power rating to shift resonance
- replace dry type capacitors with oil-impregnated capacitors.

5.5.1 Capacitors with Higher Voltage Rating

If capacitors are installed with a higher voltage rating, they will operate at lower than rated voltage. This will reduce the thermal VA burden and RMS current overload. The reactive power output will be decreased by an amount equal to the square of the ratio of the operating voltage and rated voltage and, therefore, the rated kVar must be increased accordingly.

5.5.2 Capacitor/Inductor Units

The harmonic currents flowing in the capacitors are magnified due to a parallel resonant condition near the 11th and 13th harmonics. The shunt capacitors create a parallel resonant circuit with the inductance of the system source impedance which is represented by the short circuit MVA at the point of connection. This problem can often be reduced by adding an inductor in parallel or series with the capacitor bank to move the resonance to a frequency where there are little or no harmonics. Common practice is to use a series connection tuned just below the 5th harmonic which ensures that parallel resonance occurs below any of the commonly generated harmonics.

The resonant frequency can be approximated by the simple formula,

$$\text{per unit frequency} = \left(\frac{\text{short circuit MVA}}{\text{Capacitor MVA}} \right)^{1/2}$$

At Kelsey-Hayes the parallel resonant circuit is formed primarily by the supply transformer leakage inductance and the parallel combination of all the power factor capacitors. Because there are a number of individual capacitor units, application of series inductance is not as straight forward as the case of a single capacitor bank. A centralized switched capacitor bank might be preferred to the individual motor capacitors. Each switched capacitor would require a tuning inductor. In any case this approach requires a thorough evaluation to be performed by a reputable consultant or knowledgeable power conditioning equipment supplier.

The cost of this corrective action should be considered carefully. When a capacitor/inductor installation is required for power factor correction, the pay back period may be increased significantly and power factor correction may not be as attractive as with capacitors alone. The existing capacitors will likely be replaced whether a single bank is required or not. An inductor will raise the capacitor voltage at the 60 Hz supply frequency and the existing capacitors may be overstressed. Therefore, capacitors with a higher voltage rating may be required. Regardless, the designer of the capacitor/inductor would normally consider it good practice to install a completely new unit. A capacitor/inductor unit could be double the cost of capacitors alone. Costs for consultation and analysis must also be included.

5.5.3 Capacitor with Different Reactive Power Rating

Under some circumstances capacitor size can be selected to avoid a resonance problem. The size of the capacitor is chosen to resonate at a frequency where there are little or no harmonics. For 6 pulse rectifiers, as shown in Figure 4, these occur at the triples. At Kelsey-Hayes for example, shifting the resonance from between the 11th and 13th to between the 7th and 11th might reduce the problem although this is questionable since the resonance would still increase the 7th somewhat and the 7th normally has a higher magnitude than the 11th or 13th. Also, this would require an increase in capacitance by about 1.78 times which may introduce problems with self-excitation of the induction motors to which the capacitors are connected. On the other hand, shifting the resonance to a point above the 11th and 13th harmonic say between the 13th and

17th would require a reduction in capacitance by a factor of 0.64 and reduce the power factor correction.

This technique is not preferred as a permanent solution because the resonance will shift with changes in the system impedance or if capacitors are switched out of the circuit.

5.5.4 Dry vs Oil Capacitors

Over the last 10 years, use of dry-type capacitors has become very prevalent, primarily because of the concern over the pollution of the environment which PCBs (Polychlorinated Biphenyls) used in the earlier paper dielectric oil impregnated capacitors.

Today, most manufacturers supply dry-type capacitors which are generally designed with a metallized plastic film and use no dielectric fluid. Mineral oil filled capacitors which are environmentally acceptable are still available however, and may be an alternative to the dry-type capacitors under harmonic overload conditions. It is generally felt that the oil-filled capacitors may perform somewhat better because of better heat dissipation.

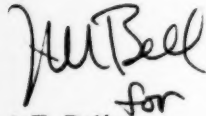
6.0 CONCLUSIONS

1. Considerable harmonic currents are generated whenever the ac or dc welders are operated.
2. The levels vary depending on which welders are operated at any given time.
3. The P.F. capacitors act as a sink for the harmonic currents which are magnified by a resonant condition close to the 11th and 13th harmonics.
4. The capacitors are operating well below permissible voltage and reactive power, including the effects of harmonics, for capacitors that conform to CSA standard CAN3-C155-M84.
5. The total rms current including harmonics exceeds the permissible continuous rating of 135% of rated current but the overload is quasi-continuous in nature due to the "on-off" operation of the welders.
6. It is not clear whether the current overload condition is within the capability of the capacitors for continuous operation.
7. Nevertheless, gradual deterioration of the capacitors and shortened life is a possibility.
8. A number of options and factors have been identified which should be considered before initiating any corrective action.

7.0 ACKNOWLEDGEMENT

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Approved:



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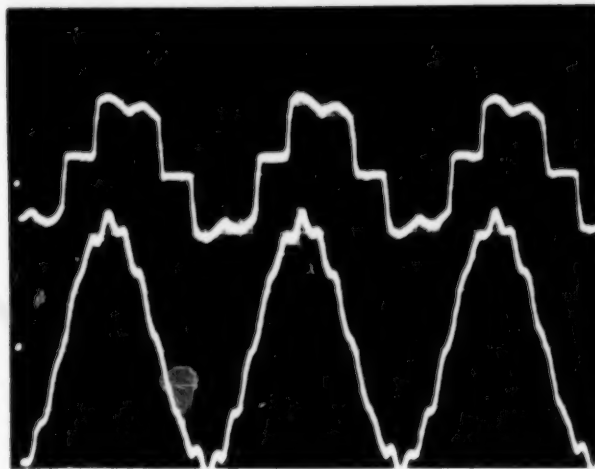


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REFERENCES

1. CSA Standard C22.2 No 190-M1985, "Capacitors for Power Factor Correction".
2. CSA Standard CAN3-C155-M84, "Shunt Capacitors for AC Power Systems".
3. ANSI/IEEE Std 18-1980, "IEEE /standard for Shunt Power Capacitors".

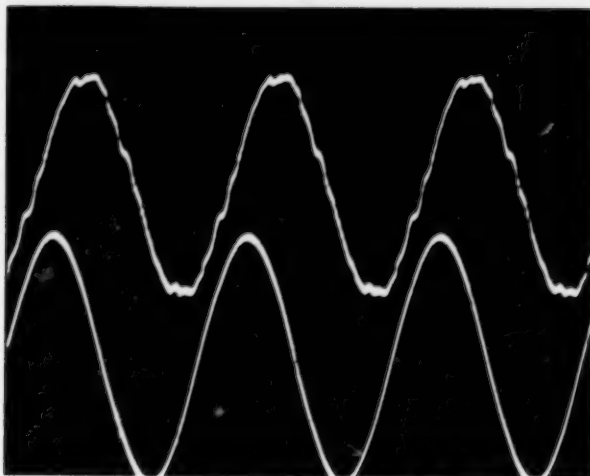


I_r , THD = 27.1%

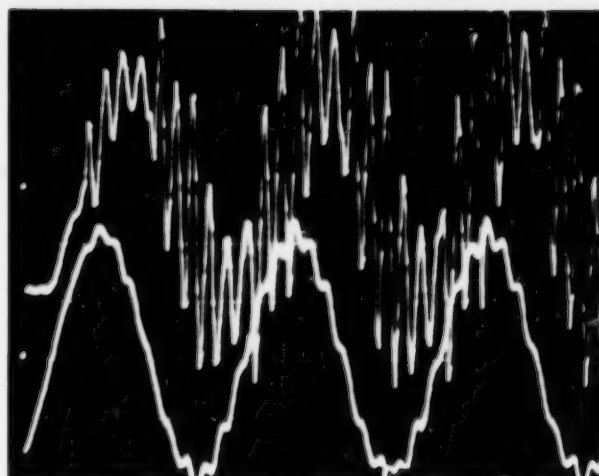
V_{r-w} , THD = 7.69%

5ms/div

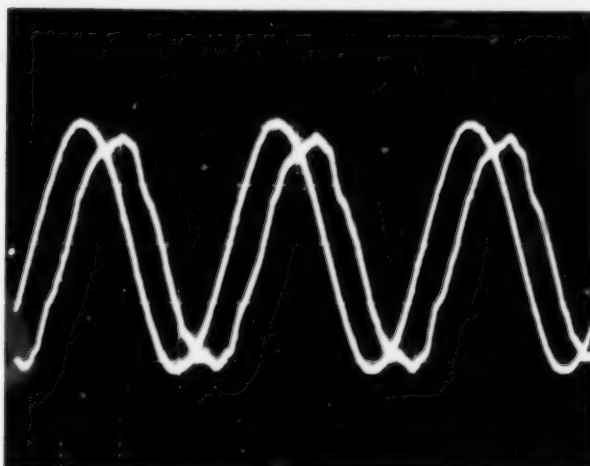
FIGURE 1
DC WELDER 'B'
Bus Current and Voltage Waveforms
April 23, 1987 14:35



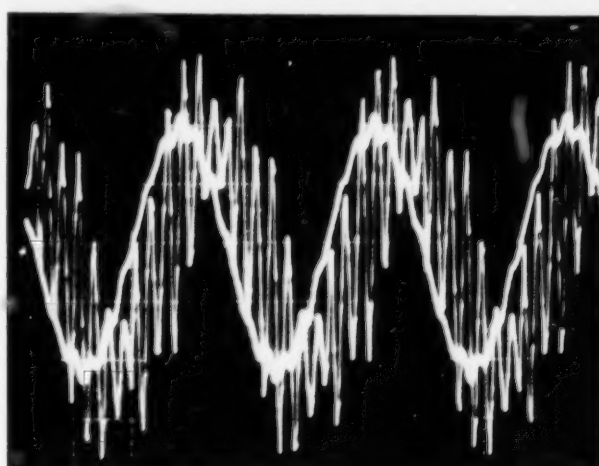
9:31 DC Welder 'off'



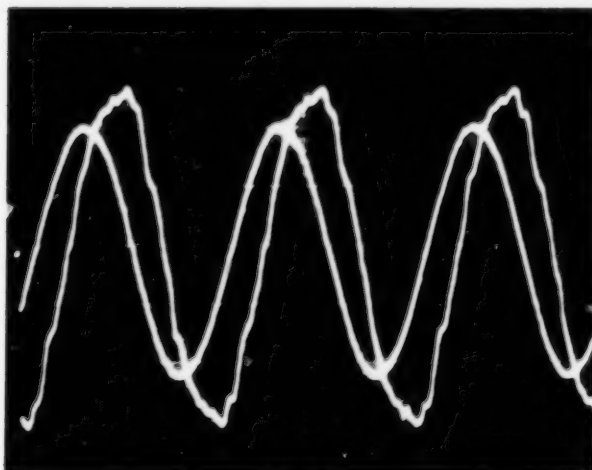
10hp/3 KVar 12:14 DC Welder 'on'
 I_r THD = 108% V_r-w THD = 9.09%



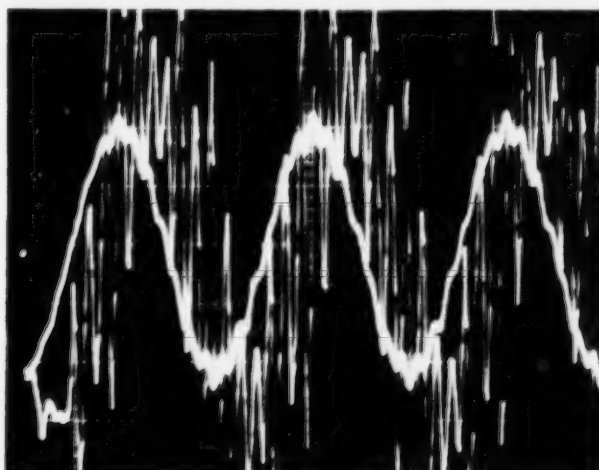
15:12 DC Welder 'off'



30hp/7KVar 15:18 DC Welder 'on'
 I_w THD = 106% V_w-b THD = 8.26%



15:26 DC Welder 'off'



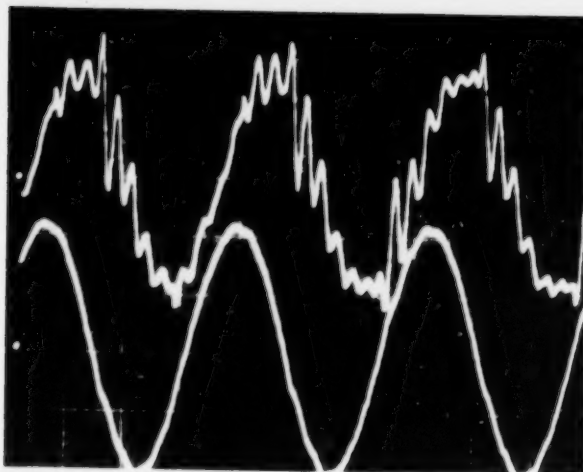
40hp/11KVar 15:30 DC Welder 'on'
 I_r THD = 108% V_r-w THD = 8.39%

FIGURE 2

DC WELDER OPERATION

Capacitor Current and Voltage Waveforms for Various
 Motor/Capacitor Combinations, April 23, 1987

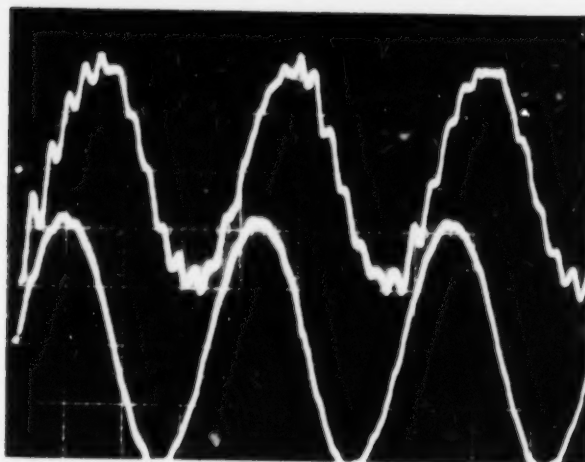
175352-RD



I) April 23, 1987 12:20

$I_r, THD = 20.9\%$

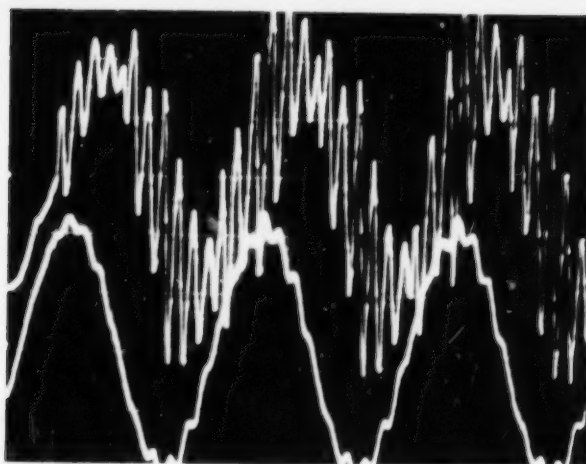
$V_{r-w}, THD = 1.77\%$



II) April 23, 1987 12:22

$I_w, THD = 6.94\%$

$V_{w-b}, THD = 1.69\%$



III) April 23, 1987 12:24

$I_b, THD = 83.9\%$

$V_{b-r}, THD = 7.91\%$

FIGURE 3
SINGLE AC WELDER OPERATION
Capacitor Current and Voltage Waveforms for
10hp/3KVar Motor/Capacitor Combination

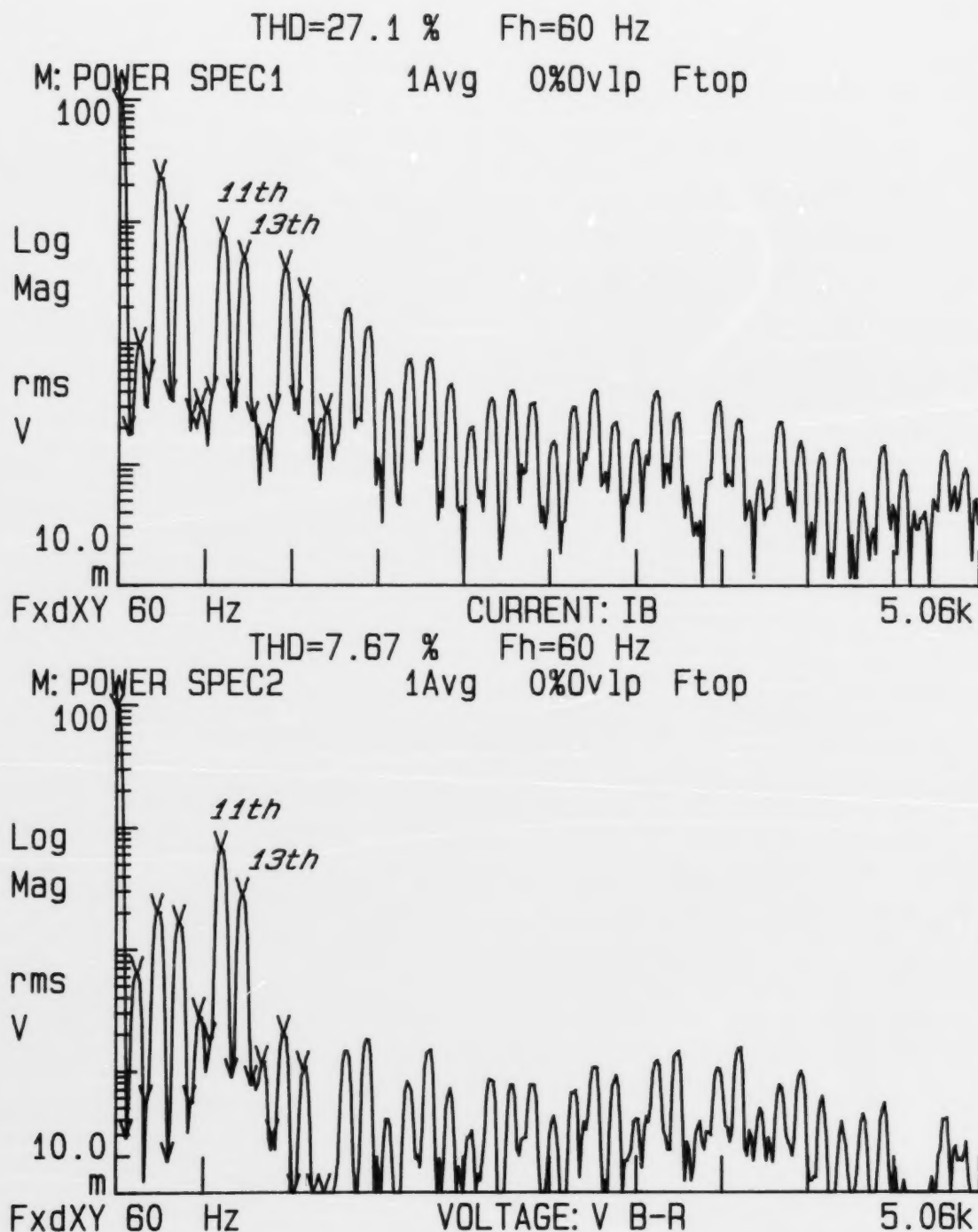


FIGURE 4 DC WELDER Voltage and Current Harmonics

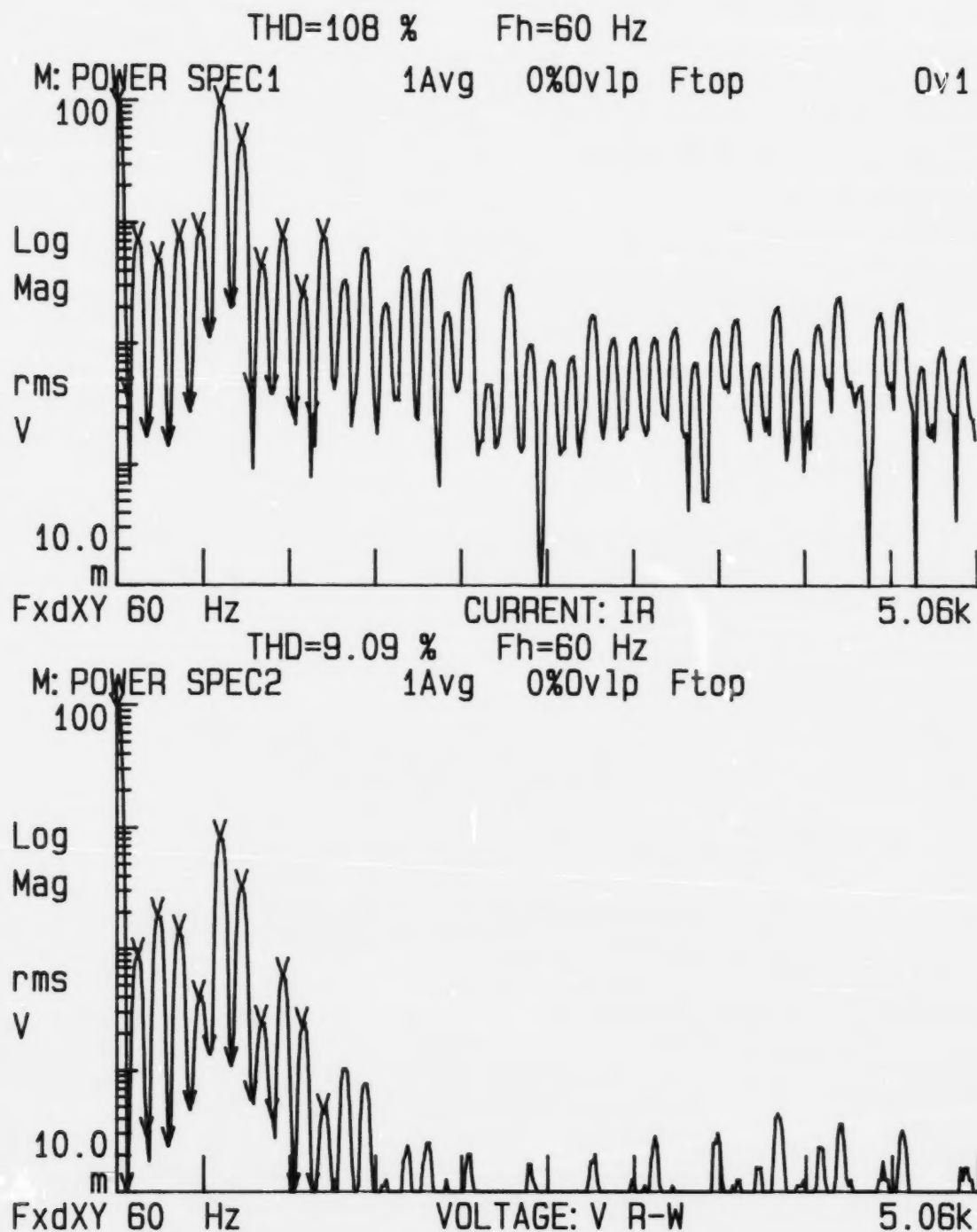


FIGURE 5 3 KVAR/10 HP UNIT

Voltage and Current Harmonics During DC Welder Operation

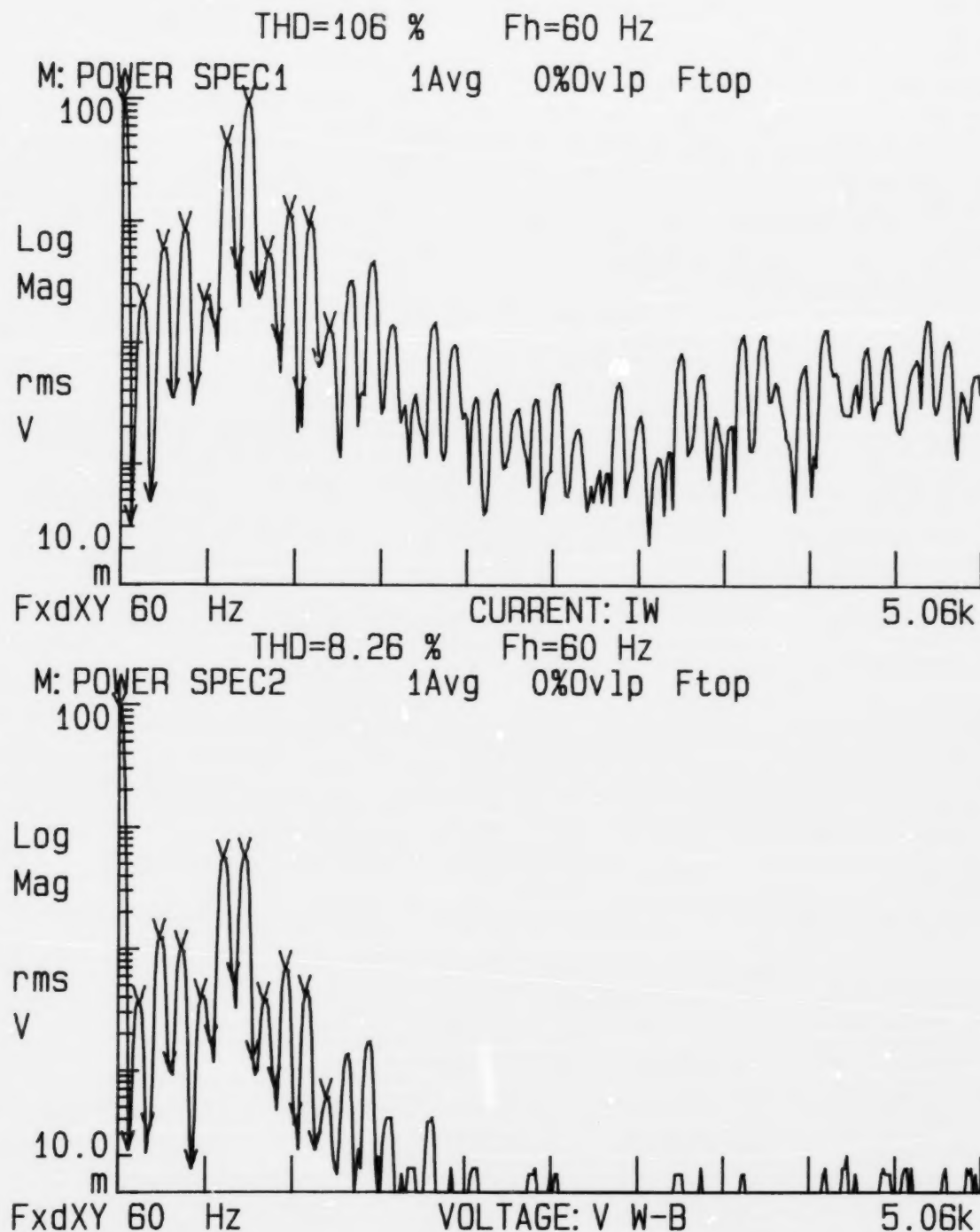


FIGURE 6 7 KVAR/30 HP UNIT

Voltage and Current Harmonics During DC Welder Operation

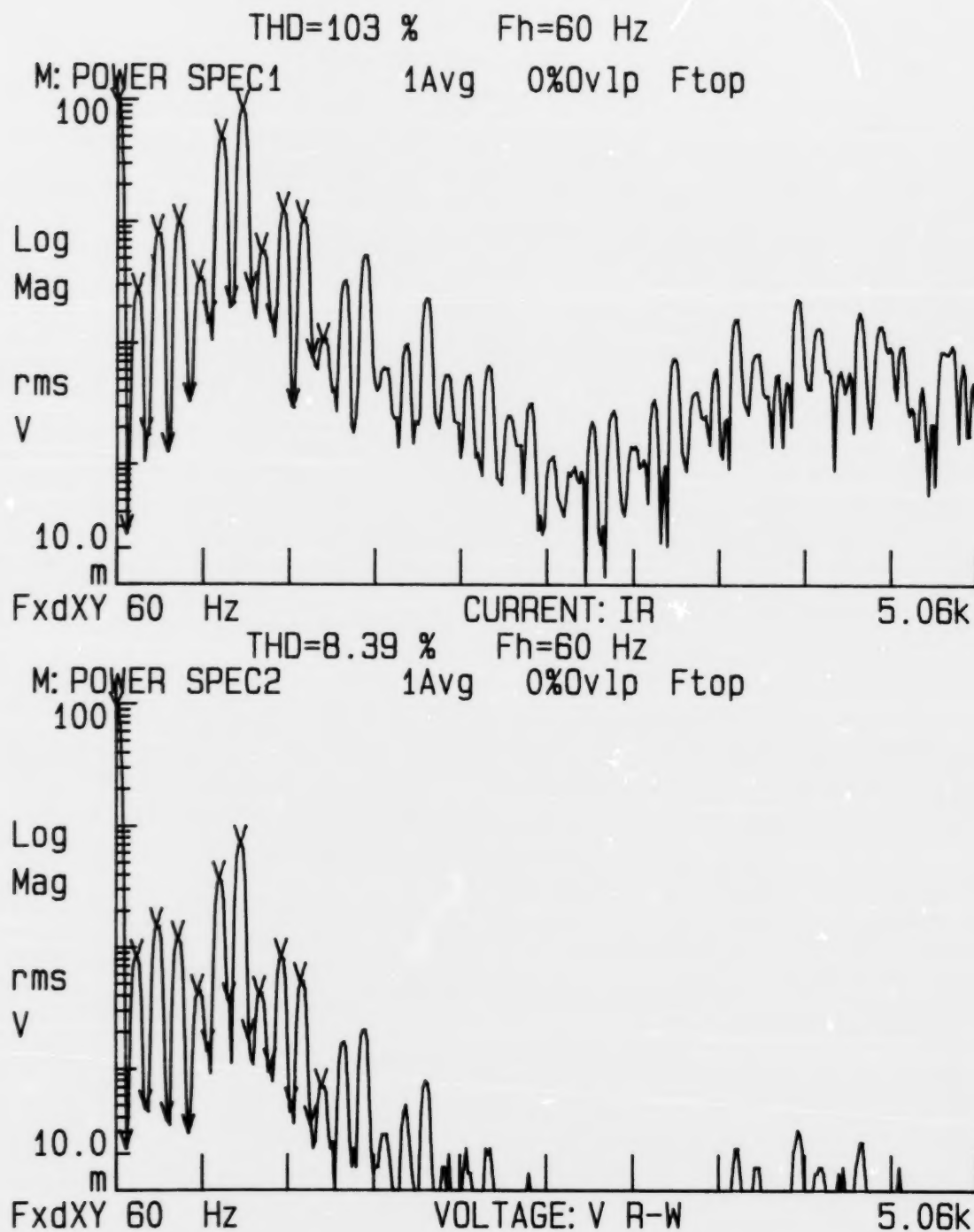


FIGURE 7 11 KVAR/40 HP UNIT

Voltage and Current Harmonics During DC Welder Operation

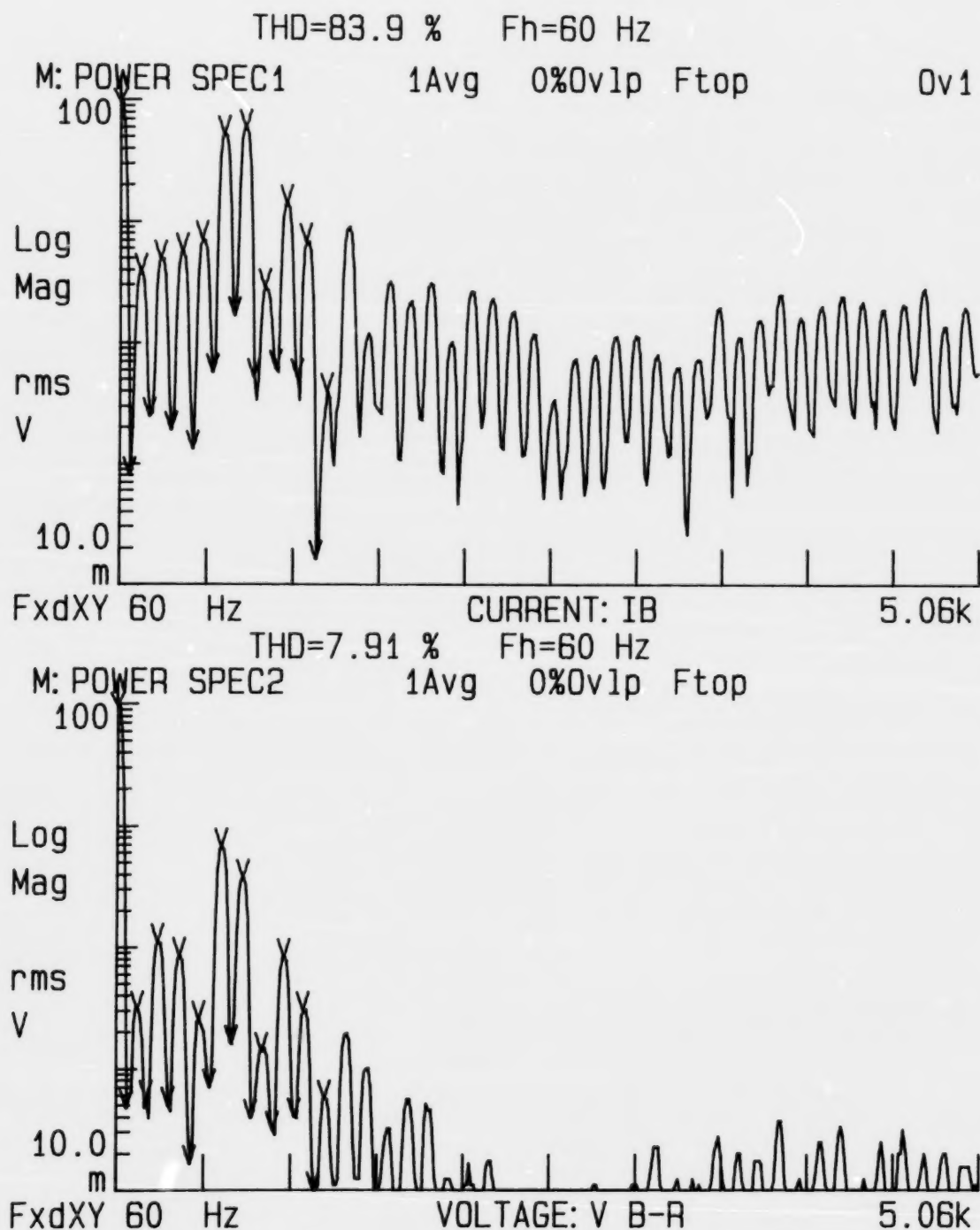


FIGURE 8 3 KVAR/10 HP UNIT

Voltage and Current Harmonics During AC Welder Operation

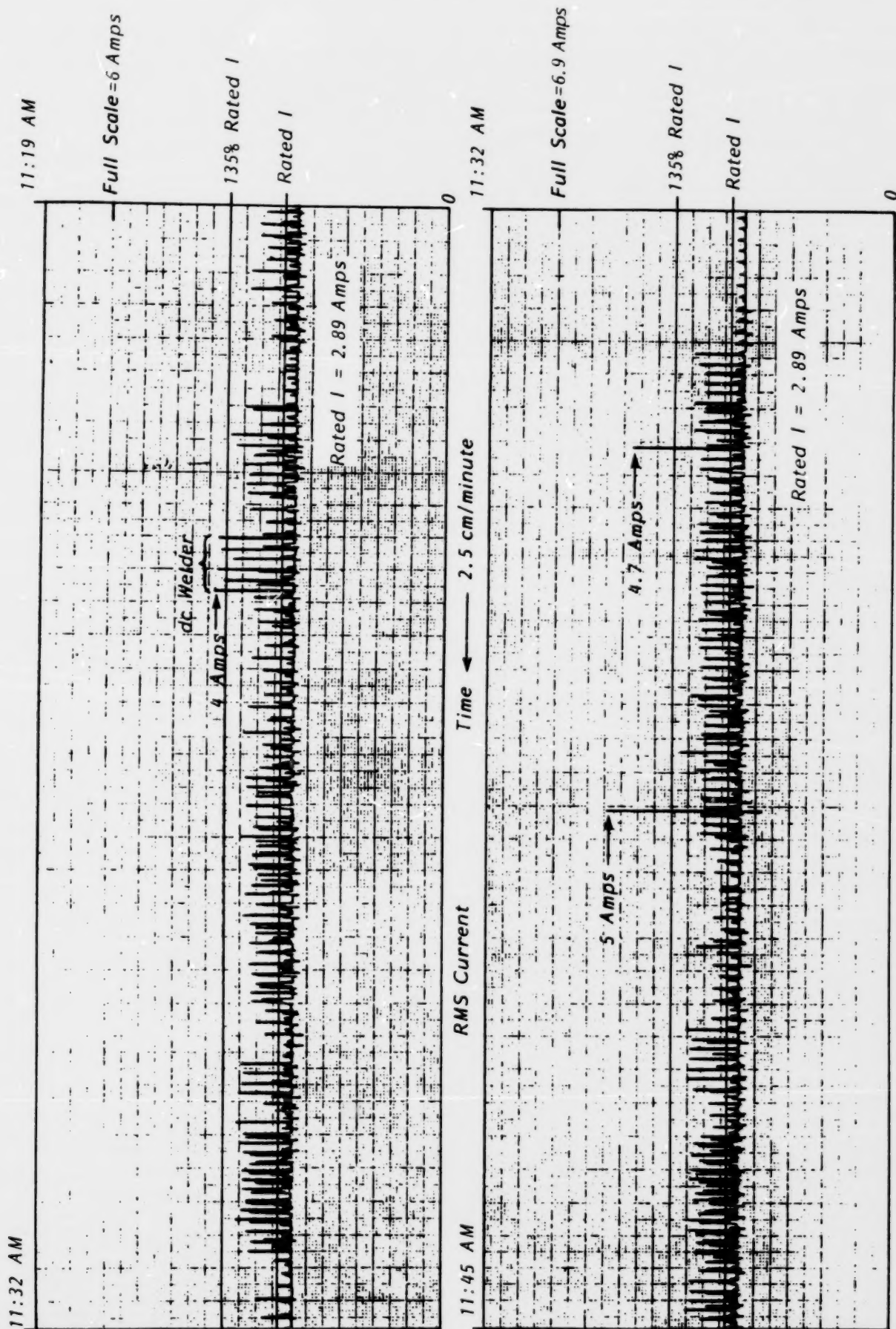


FIGURE 9
CONTINUOUS RECORDING OF TOTAL CAPACITOR CURRENT (RED PHASE)
AT 10 hp/3 kVar MOTOR/CAPACITOR UNIT, APRIL 23, 1987

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